1.1 Polarized proton acceleration at RHIC

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1.1.1 Introduction

The Relativistic Heavy Ion Collider (RHIC) is a high energy collider designed to provide not only collisions of heavy ions but also of polarized protons. Table 1 lists the RHIC machine parameters for polarized protons [1].

Table 1: Latest machine parameters for p-p collisions.

Parameter	Unit	p-p
relativistic γ, injection	…	25.9
relativistic γ, store	…	266.5
no of bunches, n_b	…	112
ions per bunch, N_b	10^{11}	2.0
emittance $\varepsilon_{N\,x,y\,95\%}$	mm·mrad	20
luminosity	$cm^{-2}s^{-1}$ 10^{30}	150
polarization,store	…	70%

Fig. 1 shows the polarized proton accelerating chain. The polarized H^- ion beam from the Optical Pumped Polarized Ion Source (OPPIS) gets accelerated up to a kinetic energy of 200 MeV in the LINAC, and then injected into the Booster through a striping foil. The Booster then accelerates the polarized proton beam to a total energy of 2.35 GeV and injects the beam into the Brookhaven AGS where beam is accelerated to 24.3 GeV.

The acceleration of polarized H- in LINAC is spin transparent. There are a total of 2 imperfection spin resonances in the Booster from its injection energy to the extraction energy. They are overcome by correcting the individual harmonics of the vertical orbit distortion. No intrinsic spin resonance is encountered during the acceleration because the vertical betatron tune in Booster is set at 4.8 just above the spin precession tune at the Booster extraction energy.

The polarized proton acceleration in the AGS encounters a total of 41 imperfection resonances and seven intrinsic resonances [2]. A 5% helical partial snake is employed to overcome all the imperfection spin resonances [3,4,5], and an rf dipole which kicks the beam at a frequency near the vertical betatron frequency is used to induce a full spin flip through the four strong intrinsic spin resonances at $G\gamma = 0 + Q_y$, $G\gamma = 12 + Q_y$ and $G\gamma = 36 \pm Q_y$ [6]. Here, G is the anomalous g-factor, γ is the Lorentz factor and Qy is the vertical betatron tune. In a circular accelerator, the spin precession tune is $G\gamma$ [2].

In RHIC, two full Siberian snakes are placed 180° apart from each other in either of the two rings to keep the spin precession tune at 0.5 so that neither imperfection resonances nor intrinsic resonances are encountered during the acceleration [1]. The Siberian snakes have worked successfully. With the proper setting of snakes and the careful control of betatron tune and closed orbit during the energy ramp, no polarization loss was observed from RHIC injection energy to 100 GeV.

The two pairs of spin rotators on either side of STAR and PHENIX also allow one to independently orient the beam polarization longitudinally at the experiments [1].

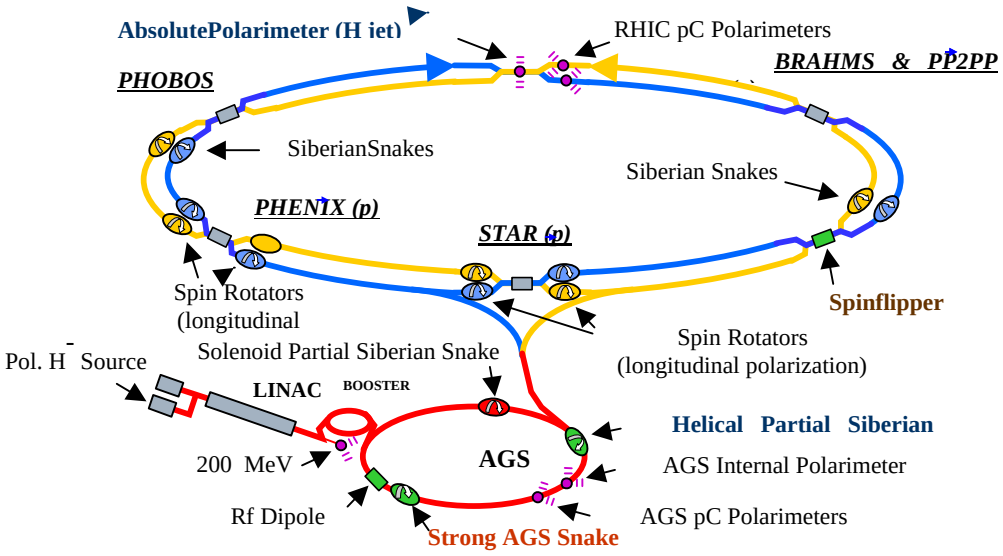

Figure 1: Polarized proton acceleration chain

1.1.2 Challenge for accelerating polarized protons in RHIC

1.1.2.1 *Polarization*

Even with the help of full snakes, beam polarization can still get lost if the vertical betatron tune satisfies the snake resonance condition as shown in Eq. 1. This type of resonance was first described by S.Y.Lee and S. Tepekian [7].

$$mQ_y = Q_s + k \qquad (1)$$

Here, Q_s is the spin precession tune, m and k are integers. Depending on whether m is an even integer or an odd integer, a snake resonance is either an even order resonance or an odd order resonance. In general, an odd order resonance is driven by the intrinsic spin resonance. An even order resonance is due to the overlap of a strong intrinsic spin resonance with the nearby imperfection spin resonance [2]. Both types of snake resonances were observed in RHIC. Fig. 2 shows the tune scan of beam polarization at energy of $G\gamma = 63$. The snake resonance at Q_y=7/10 is evident.

To avoid snake resonances, it is very critical to have both the vertical orbit distortion as well as the betatron working point under control. Currently, the RHIC polarized proton's working point is set at (0.72, 0.73) through the entire energy ramp up to an energy of 100 GeV.

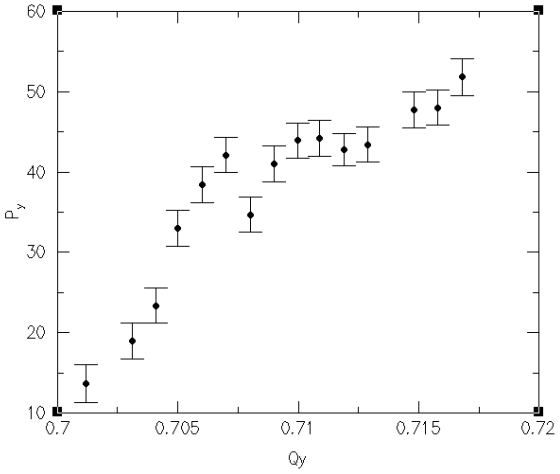

Fig. 2: snake resonance at Q_y=0.7

With the current RHIC BPM (Beam Position Monitor) system, an rms value of 0.5 mm vertical orbit distortion has been achieved. To preserve the polarization beyond 100 GeV, the vertical orbit distortion needs to be controlled within 0.3 mm. An re--alignment of the whole ring is scheduled during the summer shutdown of 2005.

1.1.2.2 *Luminosity*

Currently, the polarized proton luminosity in RHIC is limited by the beam-beam interaction [8] as well as achievable bunch intensity from the AGS in order to maintain the maximum polarization. Three possible working points were carefully studied during the RHIC polarized proton run in 2004 and a working point at (0.695, 0.685) was chosen which optimized beam-beam effect as well as had the best polarization performance [8].

In the past, RHIC also experienced a limitation on the total beam intensity due to the dynamic pressure rise. For the RHIC 2006 run, more NEG coated piped will be installed. Upgrades of the RHIC CNI polarimeters will also improve the local vacuum pressure rise. With the new 25% super-conducting partial Siberian snake in the AGS, it is expected that the beam polarization dependence on the bunch intensity will be removed. To minimize the beam-beam effects, our current plan is to reduce the non-linearities of the triplets as well as other sources. Reducing the non-linear chromaticity should also help to mitigate the beam-beam effect. A 10 Hz vibration of the beam orbit is also observed in RHIC [9] and a feedback system to compensate the 10 Hz vibration of the local orbit at the collision point has been tested and is now being implemented for the two interaction regions [10].

1.1.3 RHIC performance

The polarized proton beam acceleration in RHIC was first started in 2000. Table 2 lists the milestones of the RHIC polarized proton development over the past years.

The RHIC polarized proton beam run in 2000 was dedicated to prove the principle of Siberian snake with only one snake installed in the RHIC Blue ring. Since the AGS stable spin direction is vertical and the RHIC stable spin direction with only one full snake lies in the horizontal plane, the polarized proton beam was injected with the snake off. The snake was then adiabatically turned on in order to preserve the beam polarization. A non-zero radial polarization was then measured and confirmed that the snake was working properly.

Table 2: RHIC spin program milestone

	Milestone
2000	- New polarized proton source(OPPIS) commissioned - One snake was installed in the sector 9 in Blue ring. - CNI polarimeter in Blue installed and commissioned
2002	- All snakes for both rings installed and commissioned - CNI polarimeter in Yellow installed and commissioned
2003	- Spin rotators installed and commissioned - provided longitudinal polarizations at STAR and PHENIX for physics data taking
2004	- RHIC absolute polarimeter using Hydrogen Jet target installed and commissioned - AGS 5% helical warm snake installed and commissioned - RHIC new working point was commissioned
2005	- New superconducting solenoid was installed in the polarized source OPPIS - AGS helical cold snake was installed and commissioning was started - Polarized proton beam in RHIC was accelerated to 205 GeV with 30% polarization measured at this energy

The RHIC polarized proton run in 2003 showed that the luminosity performance was limited by the beam-beam effect. In order to mitigate the beam-beam effect, couple of new working points were investigated and commissioned during the RHIC 2004 run.

With the 300 m of NEG coated pipes installed during the summer shut-down time of 2004. the RHIC 2005 polarized proton run achieved a total of 106 bunches per ring with 0.9×10^{11} protons per bunch. The improvement of the online model as well as the RHIC BPM system also improved the polarization transmission efficiency.

During the RHIC 2005 polarized proton run, polarized proton beam was also first accelerated to 205 GeV. A polarization of 30% was measured in both rings at 205 GeV with a measured polarization of 50% at injection. The polarization measurement during the energy ramp confirms that the polarization loss occurred beyond 100 GeV.

Table 3 shows the achieved performance of RHIC during the past polarized proton runs.

Table 3: RHIC achieved performance

Parameter	Unit	2002	2003	2004	2005
No. Of bunches	…	55	55	56	106
protons/per bunch	10^{11}	0.7	0.7	0.7	0.9
store energy	GeV	100.2	100.2	100.2	100.2
β*	m	1	1	1	1
peak luminosity	$10^{30}cm^{-2}s^{-1}$	2	6	6	10
average luminosity		1.5	3	4	6
Time in store	%	30	41	38	56
average polarization, at store	%	15	35	46	47

1.14 Acknowledgement

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1.14.1 References

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